An Overview of Ciao
(and its uses of DataLog in Program Analysis/Optimization)

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The Ciao Development Team

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Motivation and Approach

- Objectives:
  - Next-generation, high-level, *multiparadigm* programming language: Ciao.
  - *Program development environments which perform, as part of compilation*:
    - *Verification / debugging*
      (i.e., detect bugs and offer guarantees *of safety, reliability, and efficiency.)*
    - *Optimization (optimized compilation, parallelization, ...).*

    Using throughout techniques that are at the same time *rigorous* and *practical*.
  - Apply in a real system, with users –reality check!
  - Support also mainstream languages (e.g., Java / Java bytecode).
- Several uses of Datalog and related techniques.

Ciao Packages and Paradigms

- Built in layers over a small, LP-based *kernel*:
  - "Packages" provide *syntactic and semantic extensions and restrictions* on a per-module basis.
- *Logic programming:*
  - Certainly ISO-Prolog (one of the popular Prologs) –but *via a library*; and also:
  - Pure LP, *ASP (ASP-Prolog, Pontelli et al.), constructive negation,* ...
  - Various comp. rules: breadth-first, iterative-deepening, Andorra, *tabling*, etc.
- *Functional programming:*
  - Function definitions and function calls and functional syntax for predicates.
  - *Higher-order* and *lazyness* for functions and predicates.
- *Constraint programming:* clpr, clpq, fd, Leuven CHR.
- *Objects*.
- *Concurrency, parallelism, distributed execution*.
- *Assertion language*, consistent across paradigms; with many uses!

+ many other packages: type systems, records, *PiLLoW, RDF, XPath,* DSLs, ...

Some Uses of Datalog and Related Technology

- Intermediate representation for several Ciao analyses.
  - Groundness (mode) analysis: `def`, BDDs.
  - Definiteness propagation in analysis of (C)LP.
  - Assertion checking: comparator.
  - VC generation / checking in Abstraction Carrying Code.
  - Simplification of parallelization conditions.
- Also for Java: nullity, aliasing / sharing, resource usage.
- Simple solvers based generally on tabling.
- Bottom-up fixpoint evaluators also used in, e.g., shape / type inference.
  - Uses magic sets, etc.
- ASP modules (ASP-Prolog, Pontelli et al.).

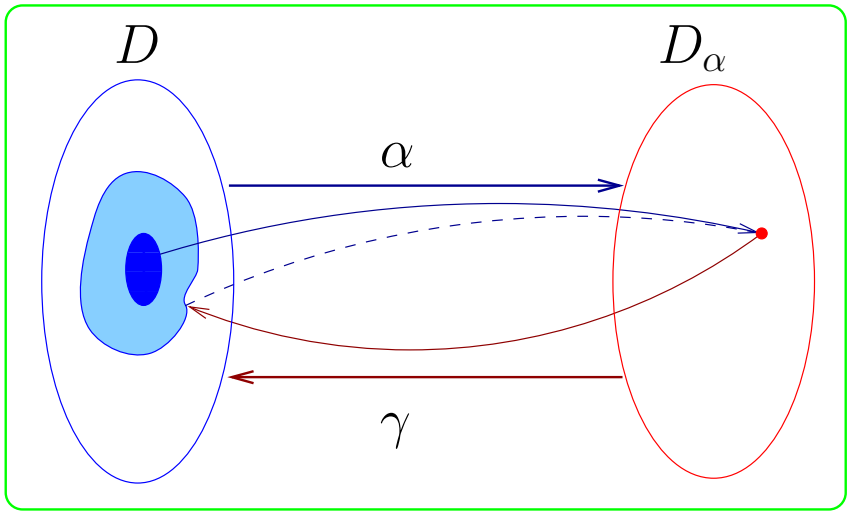
+ All tools written in Ciao (= Datalog++++ `:-)`).

Program Analysis and Optimization in Ciao

- Compute Safe over- and/or under-approximations of program semantics, $[\![P]\!]_{\alpha^+}$ or $[\![P]\!]_{\alpha^-}$
  generally based on *modular, polyvariant abstract interpretation*:

  $\forall x \in D:\ \gamma(\alpha(x)) \supseteq x$, and
  $\forall y \in D_\alpha:\ \alpha(\gamma(y)) = y$.

  $\mathrm{lfp}(S_P^\alpha) = [\![P]\!]_\alpha \supseteq \alpha([\![P]\!])$ terminates.



- Apply such approximations to verification, optimization.
- Domains: types, modes, pointer sharing, cost, sizes, termination, determinacy, non-fail, ...

Verification and Diagnosis via Abstract Interpretation [AADEBUG'97]

- Program verification/diagnosis: compare $[\![P]\!]$ with intended semantics $\mathcal{I}$ e.g.:

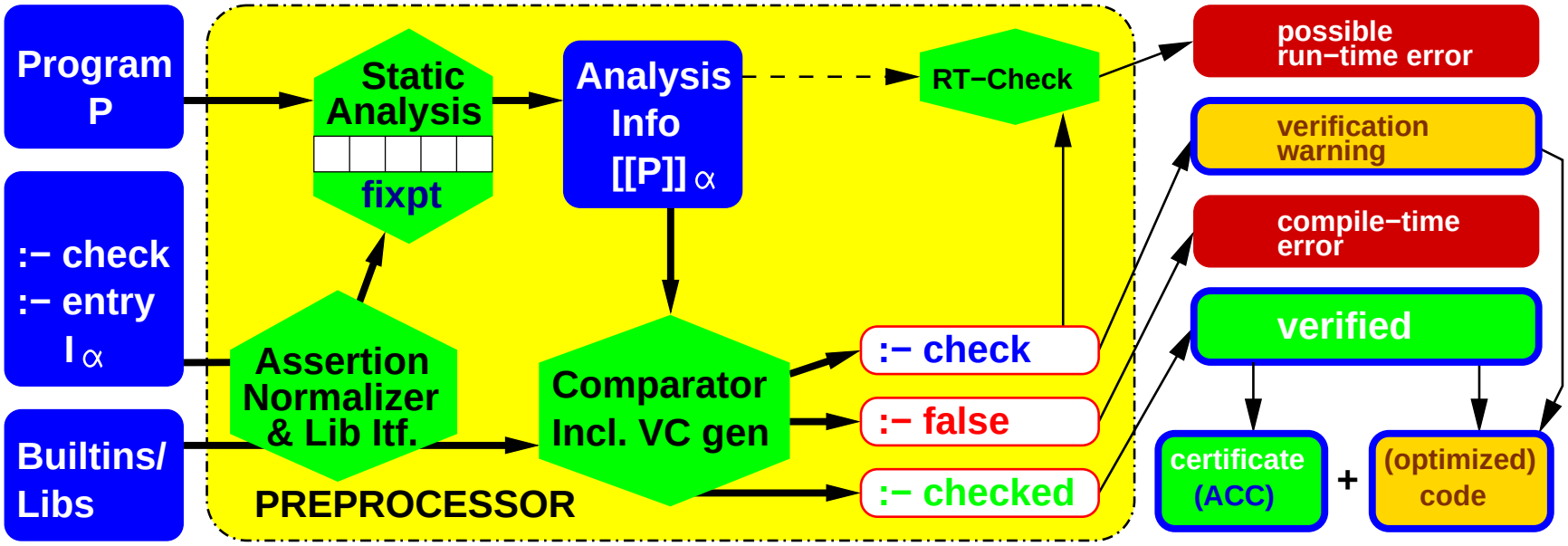
P is *partially correct* w.r.t. $\mathcal{I}$ iff	$[\![P]\!] \subseteq \mathcal{I}$
P is *complete* w.r.t. $\mathcal{I}$ iff	$\mathcal{I} \subseteq [\![P]\!]$
P is *incorrect* w.r.t. $\mathcal{I}$ iff	$[\![P]\!] \not\subseteq \mathcal{I}$
P is *incomplete* w.r.t. $\mathcal{I}$ iff	$\mathcal{I} \not\subseteq [\![P]\!]$

- Usually, only partial descriptions of $\mathcal{I}$ are available, typically as *assertions*.
- *Problem:* difficulty in computing $[\![P]\!] \rightarrow$ use *abstract interpretation* to compute a *safe approximation* $[\![P]\!]_{\alpha^+}$ $[\![P]\!]_{\alpha^+}$ indicates $[\![P]\!]_\alpha \supseteq \alpha([\![P]\!]$.

Property	**Definition**	**Sufficient condition**
P is partially correct w.r.t. $\mathcal{I}_\alpha$ if	$\alpha([\![P]\!]) \subseteq \mathcal{I}_\alpha$	$[\![P]\!]_{\alpha^+} \subseteq \mathcal{I}_\alpha$ if
P is complete w.r.t. $\mathcal{I}_\alpha$ if	$\mathcal{I}_\alpha \subseteq \alpha([\![P]\!])$	$\mathcal{I}_\alpha \subseteq [\![P]\!]_{\alpha^=}$
P is incorrect w.r.t. $\mathcal{I}_\alpha$ if	$\alpha([\![P]\!]) \not\subseteq \mathcal{I}_\alpha$	$[\![P]\!]_{\alpha^=} \not\subseteq \mathcal{I}_\alpha$, or $[\![P]\!]_{\alpha^+} \cap \mathcal{I}_\alpha = \emptyset \wedge [\![P]\!]_\alpha \neq \emptyset$
P is incomplete w.r.t. $\mathcal{I}_\alpha$ if	$\mathcal{I}_\alpha \not\subseteq \alpha([\![P]\!])$	$\mathcal{I}_\alpha \not\subseteq [\![P]\!]_{\alpha^+}$

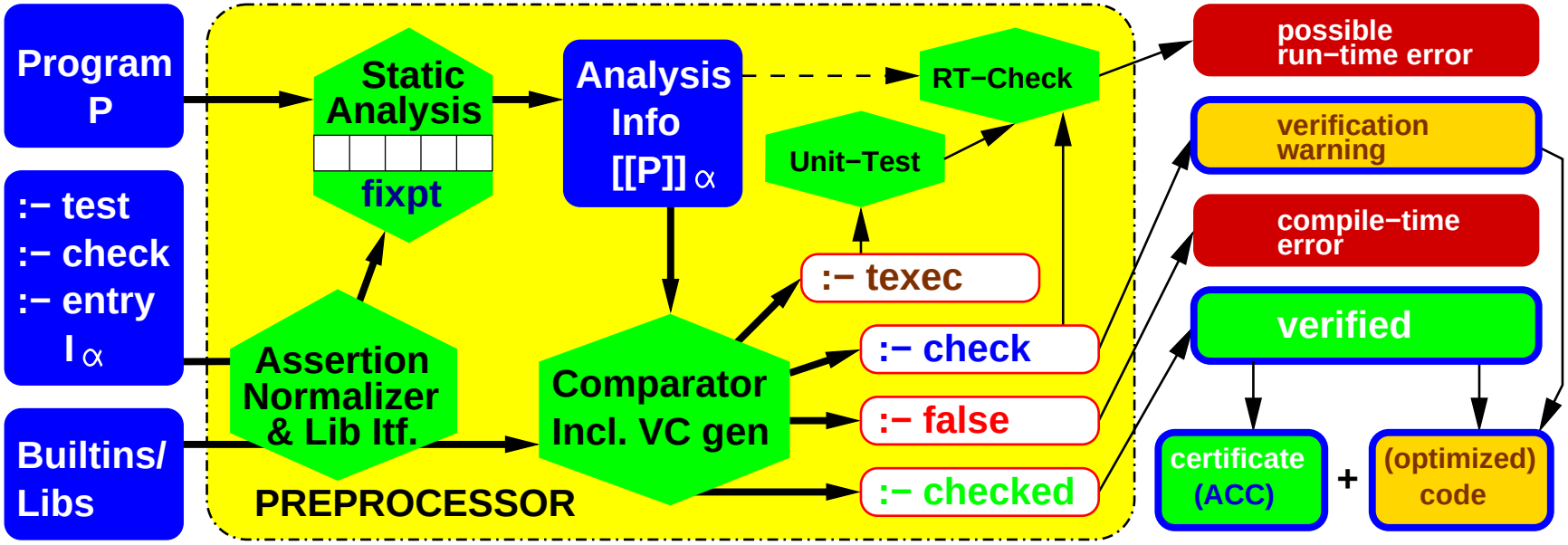
- Specially attractive if compiler computes (most of) $[\![P]\!]_{\alpha^+}$ anyway.

Verification/Diagnosis Framework (CiaoPP) [AADEBUG'97]



- I_α (partial spec.) provided via a language of *optional assertions*.
  - State properties at relevant point (pre, post, global, pp).
  - Talk about "properties," predefined or user-defined (in the source language).
- Types, modes, pointer sharing, cost, sizes, termination, determinacy, non-fail, ...

Verification/Diagnosis Framework (CiaoPP) [AADEBUG'97]



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Assertion Language: Properties

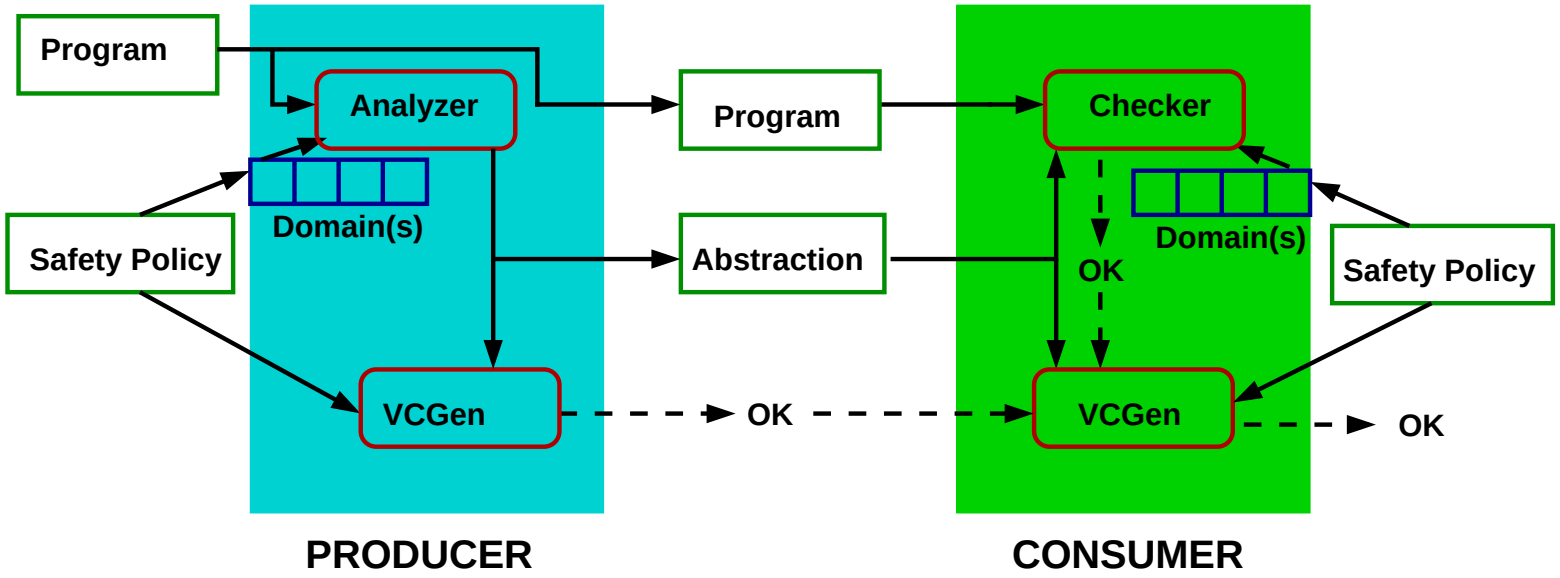
```
:- regtype list/1.                          | :- regtype list/1.
list([]).                                   | list :=  [] | [_|~list].
list([_|Y]) :- list(Y).                     |_____________________________
____________________________________________| :- regtype color/1.
:- prop sorted/1.                           | color := green | blue | red.
sorted([]).                                 |_____________________________
sorted([_]).                                | :- regtype peano_int/1.
sorted([X,Y|Z]) :- X>Y, sorted([Y|Z]).      | peano_int := 0 | s(~peano_int).
```

- Arbitrary predicates in restricted logic (a subset of Ciao).
- Some conditions on them: termination, no instantiation, ...
- Many predefined in system libs, some of them “native” to an analyzer.
- Can also be user-defined.
- Should be visible in the module and “runnable:” they will be used also as run-time tests! (but the property may be an approximation itself).
- *Types* are a special case of property (e.g., `regtype`s).
- But also, e.g., argument sizes, instantiation states, sizes, cost, ...

Assertion Language: *Pred* Assertions

- `:- pred` *PredPattern* `[ :` *Pre* `] [ =>` *Post* `] [ +` *Comp*`].`
  - *Closed* on calls: cover all uses of a predicate (they imply a calls assertion).
  - Assertion *status*: `check`, `true`/`false`, `trust`, `checked`.
- Some examples, and some syntactic sugar:
  - `:- pred qsort(X,Y) => sorted(Y).`
  - `:- pred qsort(X,Y) : list(int) * var => sorted(Y) + (is_det,not_fails).`
    `:- pred qsort(X,Y) : var * list(int)) => ground(X) + not_fails.`
  - `:- pred foo(X,Y) : ground * var => (ground(Y), X>Y) + det.`
    `:- pred foo(X,Y) : var * ground => (ground(X), X>Y).`
  - `:- trust pred is/2 => num * numexpr.`
  - `:- modedef +X : nonvar(X).`
  - `:- pred sortints(+L,-SL) :: list(int) * list(int) => sorted(SL)`
    `# "@var{SL} has same elements as @var{L}.".`

The Abstraction Carrying Code (ACC) Scheme [COCV04,LPAR04]



$[\![P]\!]_\alpha = \text{Analysis} = \text{lfp}(analysis\_step)$ | $\text{Certificate} \subset [\![P]\!]_\alpha$ | $\text{Checker} = analysis\_step$

- Scheme incorporated in `CiaoPP`, with domains: types, modes, data structure shape (including pointer sharing), bounds on data structure sizes, determinacy, termination, non-failure, bounds on resource consumption (time or space cost), ...

Big discussion (90's :-)): comparison with "classical" Types

- Allows going well beyond the "straight-jacket" of classical type systems:

"Traditional" Types	**CiaoPP Assertion-based Model [AADEBUG'97]**
"Property" language limited by decidability	Much more general property language
May need to limit programming language	No need to limit programming language
"Untypable" programs rejected	Run-time checks introduced
(Almost) Decidable	Decidable and Undecidable (and Approximated)
Expressed in a special language	(Expressed in the source language –for LP)
Types must be defined	Types can be defined or inferred
Assertions are only of type "check"	"check", "trust", ...
Type signatures and assertions different	Type signatures *are* assertions

...without giving up much (types are included as just another kind of property).

- Some key issues:

Approximation — *Suitable assertion language*

Abstract Interpretation — *Powerful abstract domains*

- Worst best when properties and assertions can be expressed in the source language (i.e., the source language supports *predicates* and *constraints*).

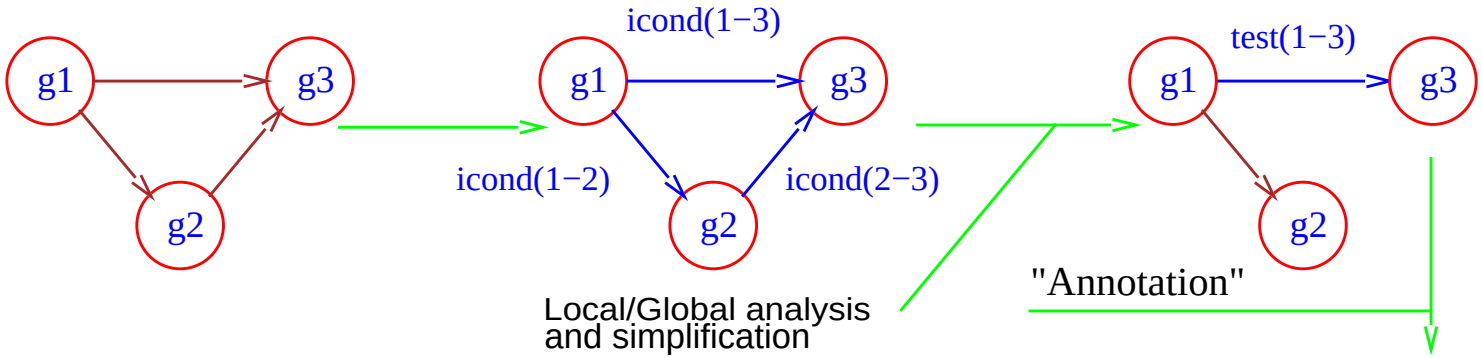
Also, optimizations

- Preprocessor architecture useful not just for verification / debugging, but also for optimization:
  - Source-level optimizations:
    - Partial evaluation, (multiple) (abstract) specialization, slicing, ...
  - Low-level (WAM) optimizations:
    - Use of specialized instructions.
    - Optimized native code generation.
  - **Parallelization.**

Automatic Program Parallelization

- Parallelization process starts with dependency graph:
  - edges exist if there can be a dependency,
  - conditions label edges if the dependency can be removed.
- Annotation: encoding of parallelism in the target parallel language:

$g_1(...)$, $g_2(...)$, $g_3(...)$



Alternative: g1, (g2 & g3)

- Global *sharing/aliasing* analysis: reduce/eliminate checks in conditions.
- Granularity control: based on cost / size analysis.

Automatic Program Parallelization (Contd.)

- *Example:*

```
qs([X|L],R) :- part(L,X,L1,L2),
               qs(L2,R2), qs(L1,R1),
               app(R1,[X|R2],R).
```

Might be annotated in &-Prolog (or Ciao Prolog), using local analysis, as:

```
qs([X|L],R) :-
         part(L,X,L1,L2),
         ( indep(L1,L2) ->
              qs(L2,R2) & qs(L1,R1)
         ;    qs(L2,R2) , qs(L1,R1) ),
         app(R1,[X|R2],R).
```

Global analysis would eliminate the `indep(L1,L2)` check.

Other Related Recent Work

- Framework adapted to Java and Java bytecode (Mobius):
  - Developed specific framework for Java/Java bytecode .
  - Analysis/validation of Java bytecode via P.Eval. of interpreter .
- Scalability, modularity .
- ACC:
  - Reduced certificates .
  - Incremental ACC (and other advanced PCC scenarios) .
- Extension of cost analysis to *time* bounds .
- Cost analysis of Java bytecode
- Extension to generic user-defined resources (Prolog and Java).
  - Examples: bytes sent over Internet, files open, DB accesses, etc.
- Abstract diagnosis.

(+ IMDEA-Software Development Technology Institute!)

Some Members of The Ciao Forge

- Ciao is really a widely distributed collaborative effort:
  - Directly within the CLIP Group:

    M. Hermenegildo, K. Muthukumar, M. García de la Banda, F. Bueno, G. Puebla, M. Carro, D. Cabeza, P. López-G., E. Albert, J. Navas, P. Chico, A. Casas, J. Correas, R. Haemmerlé, M. Méndez, J. Morales, E. Mera, C. Ochoa, P. Pietrzak, P. Arenas, S. Genaim

  - Plus lots of contributors worldwide:

    G. Gupta (UT Dallas), E. Pontelli (NM State University), P. Stuckey and M. García de la Banda (Melbourne U.), K. Marriott (Monash U.), M. Bruynooghe, A. Mulkers, G. Janssens, and V. Dumortier (K.U. Leuven), S. Debray (U. of Arizona), J. Maluzynski and W. Drabent, (Linkoping U.), P. Deransart (INRIA), J. Gallagher (Roskilde University), C. Holzbauer (Austrian Research Institute for AI), M. Codish (Beer-Sheva), SICS, ...

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All papers can be found on line at: `http://clip.dia.fi.upm.es/clippubsbyyear` and `http://clip.dia.fi.upm.es/clippubsbytopic`

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